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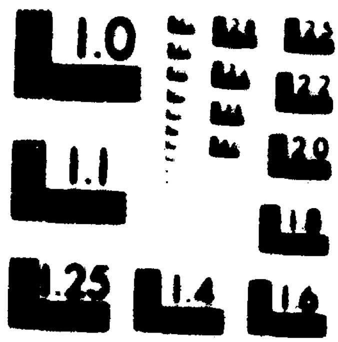
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The characterisation of the nozzle guide vane inlet and exit conditions in the Oxford University Isentropic Light Piston Tunnel fully 3-D annular rotating stage has been undertaken. Measurements included hot wire anemometry and pressure Mach number distributions. Preparations for the rotor heat transfer instrumentation data acquisition hardware and software are also in progress.

Further development of a numerical model to predict the effects of wake passing and transition is reported. The convection of the wake through the passage is predicted, allowing for estimations of the expected times for which the boundary layer is disturbed by the wake fluid. The new model for the random generation and subsequent growth and convection of the turbulent spots produces a time-resolved prediction of the intermittent heat transfer signals by use of a time-marching procedure. By superimposing the two numerical models it is possible to simulate the measured instantaneous heat transfer characteristics and to estimate the effective average intermittency along the blade surface and compare the results to the measured intermittency values.

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R. W. Ainsworth
Dept. of Engineering Science
Oxford University
Oxford, England, OX1 3PJ

J. E. LaGraff
Dept. of Mechanical and
Aerospace Engineering
Syracuse University
Syracuse, NY, USA., 13244

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Preface

The second year of AFOSR-85-0295 was completed on 31st August, 1987. During the year two presentations were made involving results obtained at the end of the first year (Summer 1986). Copies of these papers were included in last year's annual scientific report. Further analysis of the data proceeded with the subsequent development of numerical models for unsteady heat transfer during the wake passing and turbulent spot growth events. A draft of a paper outlining these developments is attached.

Professor LaGraff was in residence at Oxford during the year on 19th - 25th October, 1986, 10th - 15th February, 1987 and 10th May - 16th July, 1987. The graduate student from Syracuse University, Michael Izsak, arrived on 25 May, 1987 and will be in residence until 31st August, 1988. He is expected to obtain an Oxford University M.Sc. at the end of his stay.

I Introduction

The ability to successfully model the onset and progression of the boundary layer transition process is fundamental to the accurate prediction of the skin friction and heat transfer distribution on a surface such as gas turbine blades. At Reynolds numbers typical of gas turbine operation, the extent of the transition process can be a significant fraction of the surface length. Thus, failure to accurately model the transition region can lead to serious errors in local heat transfer distribution and total heating load, for example. It is often the case that the development of an accurate model is preceded by the existence of detailed experimental data from a realistic simulation. An inherently complex phenomenon such as transition has eluded routine modelling for many years. The further complication introduced by the unsteady NGV/rotor wake interactions in the gas turbine environment has made the understanding of the turbine blade transition process that much more difficult.

Experiments were completed during the first year of the present grant using wide-bandwidth surface heat transfer instrumentation on a 2-D cascade turbine blade (e.g. refs. 1-5). This work provided a detailed picture of unsteady heat transfer associated with both turbulent spot growth and wake passage. Considerable modelling efforts have continued in the second year of the grand period. A numerical model has been developed which first predicts the wake interaction with the blade passage and then predicts transitional behaviour by a random generation of turbulent spots and the subsequent growth, convection and merging of the spots to eventually form a fully turbulent boundary layer. The transition model allows the generation rate, growth rate and convection rate to be independently varied in order to compare low speed flat plate data and models with the observed data on a transonic gas turbine rotor profile operating under realistically simulated engine operating conditions.

Preparations for transition experiments in a 3-D fully annular rotating stage were made during the present reporting period. This experiment would then provide the data necessary to complete the picture of the transition/wake interaction proces that has been built up by the 2-D cascade tests using a rotating bar wake simulator. This is expected to be completed during the third year.

II Experimental Program Recent Progress

The primary experimental activities for the period of this report involved preparing the pressure and hot wire instrumentation along with the supporting data logging system for the calibration of the NGV inlet and exit conditions before the rotor was assembled. The instrumentation included both rapid surface pressure measurements and hot wire anemometry. Calibration of the system with the rotor in place and the measurement of both steady and unsteady heat transfer will take place during the period following that reported in this report.

Commissioning runs were conducted in the new large scale annular test section of the Isentropic Light Piston Tunnel (ILPT) beginning in July, 1987 (Ref. 6). Only the nozzle guide vane (NGV) ring was installed at first for the purpose of investigating the performance of the new annular working section and determining the inlet aerodynamics (see Figure 1). Wall Mach number distributions were determined via static pressure tappings along the working section to confirm that the inlet flow was uniform. Figure 2 contains typical results. Mach number distributions were also determined on the NGV pressure and suction surface at the root, mid-height and tip. A mid-height distribution obtained is shown in Figure 3 compared with a 2-D inviscid code prediction. The agreement is quite good, as is run-to-run repeatability and agreement with earlier 2-D experimental work conducted on the same profile.

The final commissioning phase consisted of 'tuning' the tunnel to operate at gas-to-wall temperature ratios greater than one. This was also done with only the NGV ring installed, before the installation of the rotor. Tuning consisted of adjusting pressures, trigger levels, and other parameters over the course of repeated runs in order to obtain tunnel 'matching' and the correct Mach and Reynolds number for various temperature ratios. Total pressure and temperature loss through the annular gate valve was shown to be small.

During the commissioning phase, hot wire anemometry was utilized to determine the turbulence level and spectral content of the flow at the NGV entrance. Preliminary investigations in a low speed steady-state wind tunnel were undertaken in order to gain familiarity with the data acquisition system and estimate calibration constants. Static tests were conducted in a pressure vessel to determine the effect of pressure on the no-flow hot wire output voltage. The aim of this work is the development of empirical correlations for use in calculating turbulence levels. Initial results indicated little change in no-flow voltage at pressures above atmospheric, with an increase of about 4% above the atmospheric value for a pressure approaching that encountered at cold run design conditions.

A hot wire probe operating at an overheat ratio of 0.6 was positioned at mid-height in the NGV entrance plane. High and low pass filters for the AC signal were set at 130 Hz and 80 Hz respectively. An average turbulence level of approximately 3.3% was recorded. A typical turbulence spectrum obtained is shown in Figure 4. Typically, 98% of the turbulent energy in the flow was at frequencies lower than 20 kHz, and 70% lower than 2 kHz. Tests conducted with the wire inclined at two different angles produced nearly identical power spectra, indicating that the flow field is isotropic.

Since a possible influence on the transition process in a turbine rotor is its passage through NGV wakes, it is desirable to determine the nature of the wakes as closely as possible in terms of shape, total pressure and velocity deficit, and turbulence. This information will help clarify the physical situation as well as provide necessary background data for future investigations in this area. To this end, a traverse mechanism has been designed and tested. It is capable of automatically moving a probe radially in the NGV exit plane during a tunnel run, and can be moved manually to successive circumferential positions covering several wake widths over the course of repeated runs. In addition, a radial hot wire traverse for the

NGV inlet plane has been developed in order to further characterise upstream conditions.

III Numerical Work - Recent Progress

A new method has been developed for numerically modelling the development of turbulent spots within a laminar boundary layer. This part of the natural transition process follows from the breakdown of Tollmien-Schlichting waves into three-dimensional disturbances which distribute a number of turbulent sources at random time intervals over a region on the surface. The model performs a numerical integration of the lateral and longitudinal growth of these turbulent spots along the transition length by a time-marching procedure which models the random distribution of bursts in space and time. Each burst is characterised by leading and trailing edge propagation rates as a function of the local freestream velocity, and by a constant lateral spreading angle consistent with theoretical assumptions of conical similarity for spot growth with surface length. The rate at which the bursts are generated can be varied in the streamwise direction allowing for examination of the resulting average intermittency, defined as the fraction of time for which at a given location in the transition zone the boundary layer is in a turbulent state. The intermittency functions derived from theoretical models of turbulent burst development are seen to correspond to exponential distributions as a funtion of transition length. The exponential index is proportional to the square of this length if a Dirac delta function is used for the rate of burst generation and to the cube if a step function is assumed. A numerical verification of both of these functions was performed by the new numerical model. However, neither of these functions has been proven to represent the real distribution of bursting rate along the surface. The new model is one way of performing the transformation from bursting rate to intermittency while allowing for functional dependencies to be introduced for the numerical parameters used as input to the model. The sensitivity of the model to variations in spot production rates, propagation velocities and lateral growth angle was investigated, with most sensitivity shown to be due to the choice of production rate. The model was first validated against existing flat plate intermittency data with encouraging levels of agreement assuming that the onset point is known, and by varying the production rate to match the measured transition length. The model was then used to analyse data taken from a series of tests carried out at realistic gas turbine operating conditions, as reported in the first year of the present grant.

The experimental data from the first year had shown clearly turbulent spot activity along the blade surface for the high freestream turbulence cases. The dimensions and locations of the gauges allowed for the precise tracking of turbulent spots and permitted comparisons to be made with the model. Measured intermittency values were obtained by post-processing of the digitised heat transfer signals. Cross-correlation between adjacent heat transfer traces allowed for estimations to be made of the mean convection rate between measuring locations. The measured intermittency distributions and convection rates were compared with those predicted by the new model. It was shown that the natural transition phenomenon is dominated by the choice of bursting rate function chosen to represent the receptivity of the boundary layer to external disturbances. A more thorough treatment of this modelling is included in the draft paper of Appendix A, submitted to the ASME Gas Turbine Conference for June, 1988.

Recent Publications

1. Ashworth, D.A., LaGraff, J.E. and Schultz, D.L., "Unsteady Interaction Effects on a Transitional Turbine Blade Boundary Layer," Proceedings of 2nd Joint JSME/ASME Thermal Engineering Conference, Honolulu, March 1987.

2. Schultz, D.L., Ashworth, D.A., LaGraff, J.E., Johnson, A.B. and Rigby, M.L., "Wake and Shock Interactions in a Transonic Turbine Stage, AGARD, 68th Propulsion and Energetics Panel Meeting, Transonic and Supersonic Phenomena in Turbomachines, Munich (Neubiberg) Germany, 10-12 Sept., 1986.

3. Ashworth, D.A., "Unsteady Aerodynamics and Heat Transfer in a Transonic Turbine Stage," D. Phil. Thesis, Oxford University, 1987.

4. Ashworth, D.A., LaGraff, J.E., Schultz, D.L. and Grindrod, K.J., "Unsteady Aerodynamics and Heat Transfer Processes in a Transonic Turbine Stage," J. Eng for Gas Turbine and Power, Vol. 107, pp. 1022-1030, October 1985.

5. LaGraff, J.E., Ashworth, D.A. and Schultz, D.L., "Measurement and Modelling of the Gas Turbine Blade Transition Process as Disturbed by Wakes," submitted to ASME International Gas Turbine and Aero-engine Congress, June 1988.

6. Ainsworth, R.W., Schultz, D.L., Davies, M.R.V., Forth, C.J.P., Oldfield, M.L.G., Hilditch, M.A., Sheard, A.G., " Transient Facility for the Study of the Thermofluid-dynamics of a Full Stage Turbine Under Engine Representitive conditions," submitted to ASME International Gas Turbine and Aero-engine Congress, June 1988.

Fig. 1 Annular Rotating Stage Test Section

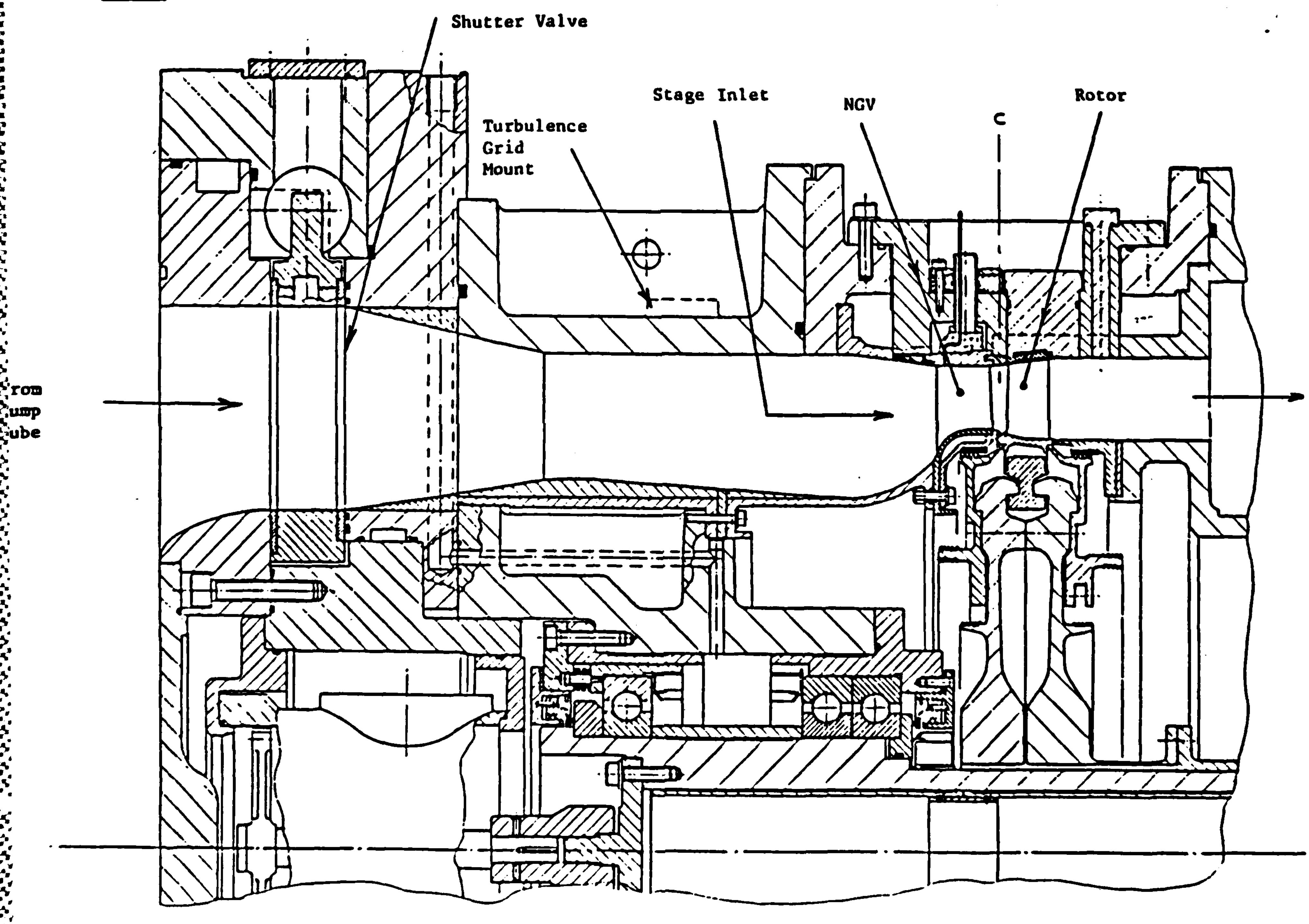


Figure 2

B23 Exit (plane C) circumferential Mach number distribution.

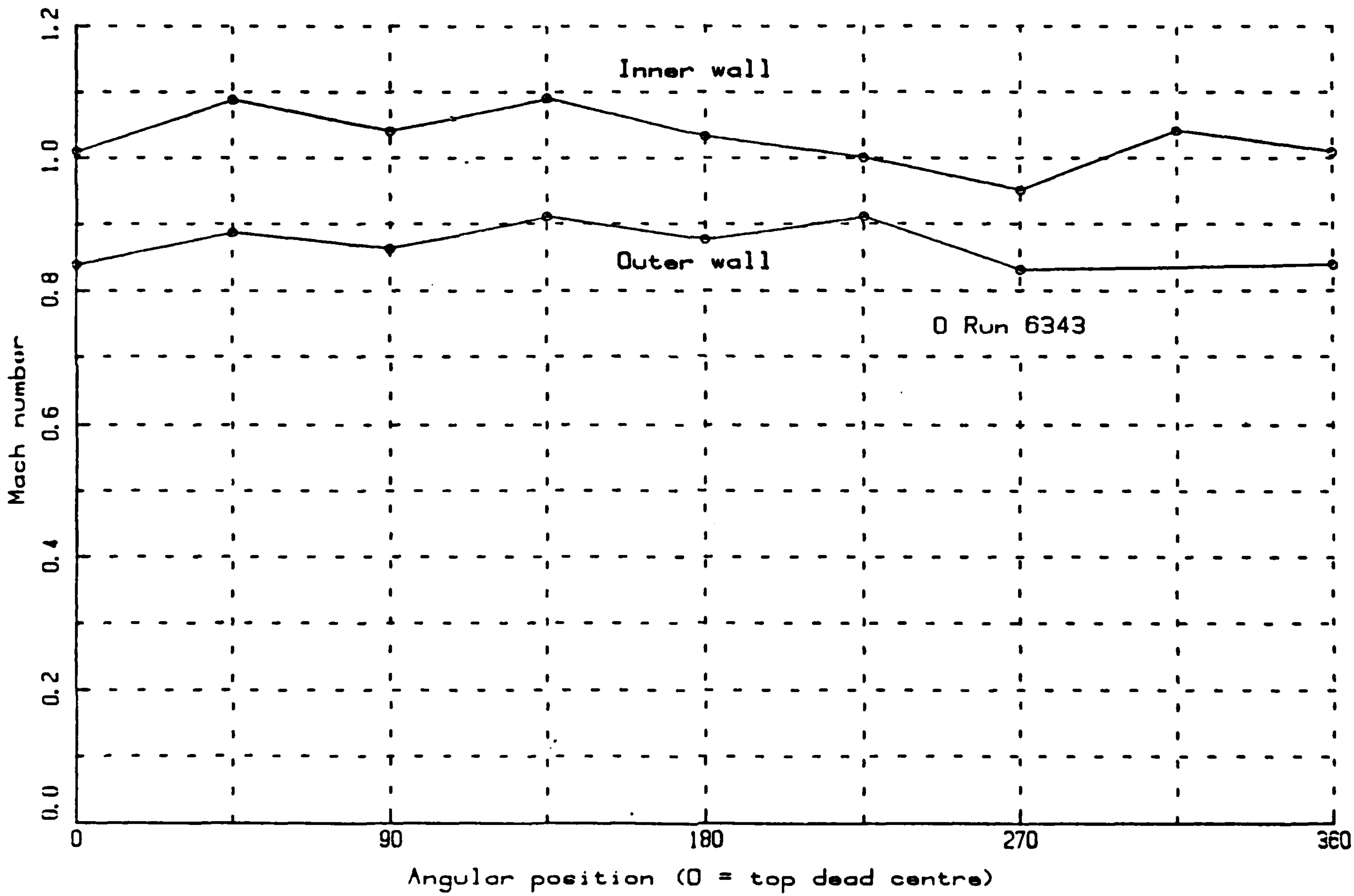


Figure 2

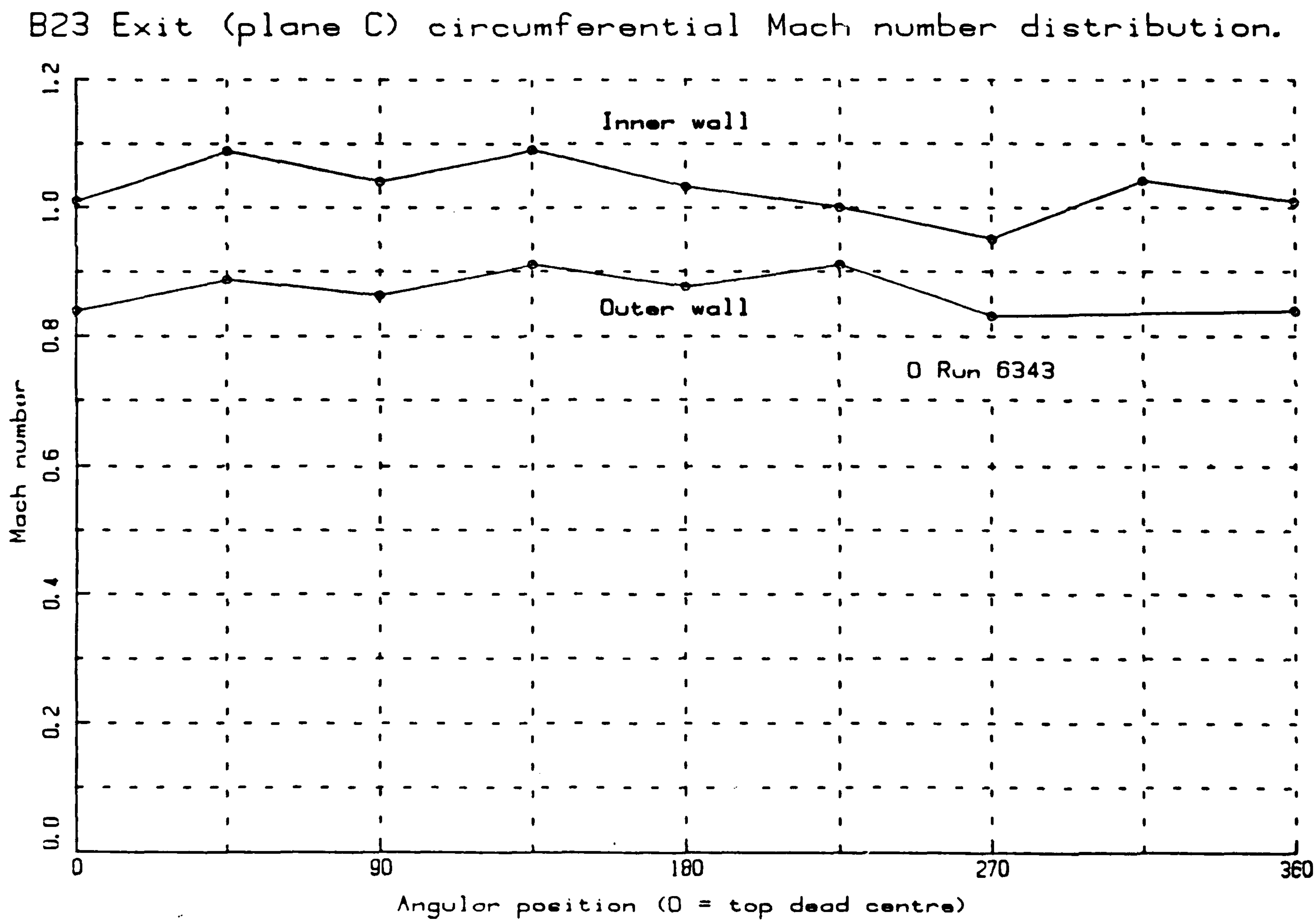

B23 Exit (plane C) circumferential Mach number distribution.
Inner wall
Outer wall
0 Run 6343
Mach number
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
90
180
270
360
Angular position (0 = top dead centre)

Figure 3 - NGV Mach Number Profiles

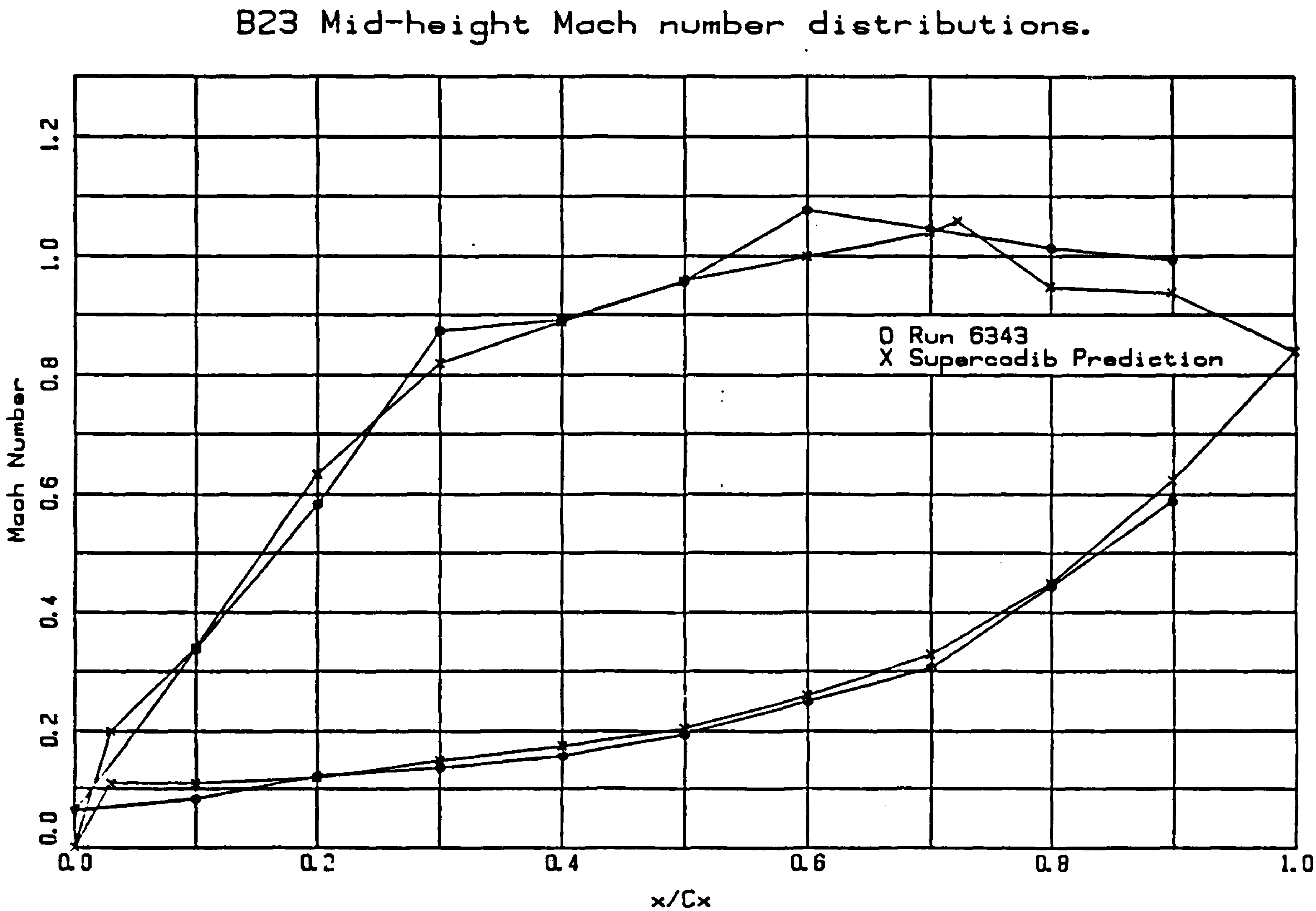
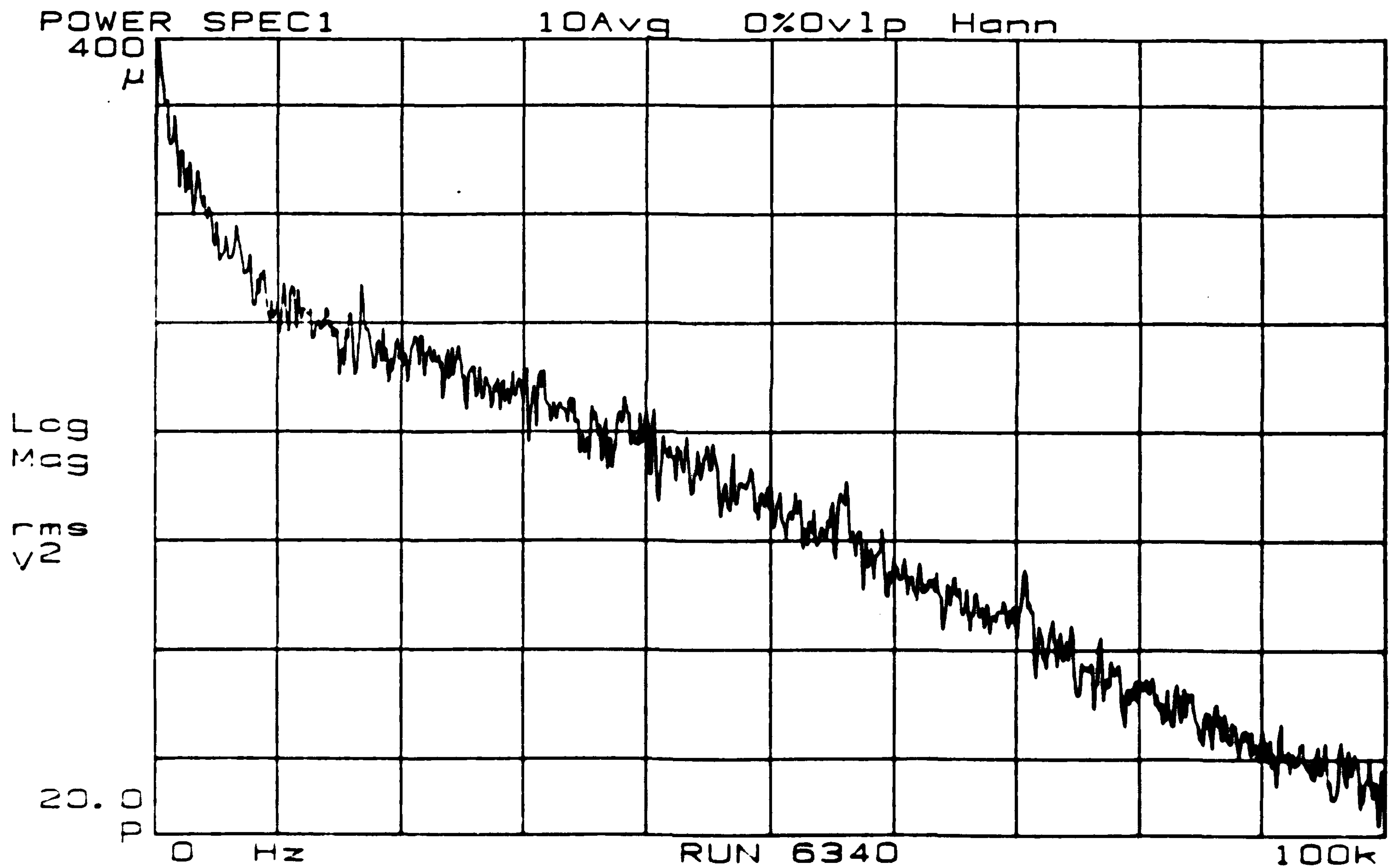


Figure 4 - NGV Entrance Plane Power Spectrum



APPENDIX

Paper submitted to ASME International Gas Turbine and Aero-engine Congress, Amsterdam, June 1988.

DRAFT

Abstract prepared for the 33rd ASME International Gas Turbine and Aero-engine Congress, 5th - 9th June, 1988

Measurement and Modelling of the Gas Turbine Blade Transition Process as Disturbed by Wakes

J. E. LaGraff[*]
Syracuse University
Syracuse
N.Y. 13244
U.S.A.

D. A. Ashworth[**]
Rolls-Royce plc
Derby
U.K.

D. L. Schultz[***]
Oxford University
Oxford
U.K.

Abstract

Heat transfer measurements have been made on a transonic turbine blade undergoing natural transition and with a simulation of the effect of NGV wake interactions. The use of wide bandwidth heat transfer instrumentation permits the tracking of individual unsteady events which were identified as being due to either the impinging wakes or to the turbulent spots occurring within the transition process. Trajectories of these events as seen by the blade surface instrumentation have been measured.

Numerical models have been developed for the effects of both types of turbulent activity. The convection of the wake through the passage is predicted, allowing for estimations of the expected times for which the boundary layer is disturbed by the wake fluid. The new model for the random generation and subsequent growth and convection of the turbulent spots produces a time-resolved prediction of the intermittent heat transfer signals by use of a time-marching procedure. By superimposing the two numerical models it is possible to simulate the measured instantaneous heat transfer characteristics and to estimate the effective average intermittency along the blade surface and compare the results to the measured intermittency values.

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[*] Member ASME, Director, Aerospace Engineering Program
[**] Section Leader, Blade Cooling Research
[***] Deceased, Formerly Professor of Mechanical Engineering

Introduction

The ability to successfully model the onset and progression of the boundary layer transition process is fundamental to the accurate prediction of the skin friction and heat transfer distribution on a surface such as gas turbine blades. At Reynolds numbers typical of gas turbine operation, the extent of the transition process can be a significant fraction of the surface length. Thus, failure to accurately model the transition region can lead to serious errors in local heat transfer distribution and total heating load, for example. It is often the case that the development of an accurate model is preceded by the existence of detailed experimental data from a realistic simulation. An inherently complex phenomenon such as transition has eluded routine modelling for many years. The further complication introduced by the unsteady NGV/rotor wake interactions in the gas turbine environment has made the understanding of the turbine blade transition process that much more difficult.

Recent developments in experimental facilities and instrumentation have resulted in significant progress in our understanding of the wake interaction problem through its effects on the time resolved and mean heat transfer rates to gas turbine blades, e.g. Doorly and Oldfield (1985b), Pheil et al. (1982), Dunn (1985) and Ashworth et al. (1985). More recently, Ashworth et al. (1987) has reported experimental results where the end stage of the transition process (3-D turbulent spot inception and growth) on a gas turbine blade under realistically simulated engine conditions has been followed with considerable detail using wide bandwidth surface heat transfer instrumentation. The onset and length of this turbulent spot region is of considerable importance to engine heat transfer code designers because this is where rapid changes in the heat transfer rate to the blade surface takes place. The existence of turbulent spot data with this level of detail provided an opportunity to test various models of this region against observations. The experiments reported also included simulated wake-passing events and thus allowed comparison with combined wake/turbulent spot models to be made. The paper presents a detailed picture of both naturally transitioning turbine blade boundary layers and transitional boundary layers disturbed by wake events. A numerical model is then described which first predicts the wake interaction with the blade passage and then predicts transitional behavior by a random generation of turbulent spots and the subsequent growth, convection and merging of the spots to eventually form a fully turbulent boundary layer. The transition model allows the generation rate, growth rate and convection rate to be independently varied to compare low speed flat plate data and models with the observed data on a transonic gas turbine rotor profile operating under realistically simulated engine operating conditions.

Experimental Approach

The tests were conducted in a transonic 2-D cascade in the Oxford University Isentropic Light Piston Tunnel (ILPT) as described by Schultz et al. (1977). The basic instrumentation technology utilized thin film heat transfer gauges as described by Schultz and Jones (1973) and wide bandwidth electrical analogue circuitry as developed by Oldfield et al. (1984). The ILPT facility is capable of routinely producing test conditions appropriate to the gas turbine hot section aero/thermodynamic environment. Specifically for the current tests, a stage inlet and outlet mach number of 0.38 and 1.18 respectively, was produced at an effective Reynolds number of 0.92×10^6 and a gas-to-wall temperature ratio of 1.5. These conditions corresponded to the "design condition of the particular profile tested. Free stream turbulence levels of < 0.8% and 3% could also be established in the test section by an upstream grid. Standard engine definitions for aerodynamic conditions were used:

$$Re = \text{Reynolds number} = \frac{\rho u_2 c_t}{\mu}$$

with μ derived from Sutherland's law and

M = isentropic Mach number u/a_1

where a_1 = sound speed = $\sqrt{\gamma R T_1}$. Subscripts 1 and 2 refer to inlet and exit conditions respectively.

The position of the thin film gauges on the model suction surface is shown in Figure 1. The gauges, 0.5 mm wide and extending 4 mm in the spanwise direction, were closely spaced (2.5 mm) to aid in the tracking of unsteady events. The narrow span length (4 mm) enhanced the sensitivity of the gauges to small scale transient events since the thin films essentially averaged heat transfer rates along their length. The electrical analogue circuits coupled with 16 channels of simultaneous high speed digital sampling instrumentation (500 KHZ) allowed for the precise tracking of unsteady events at an effective bandwidth of nearly 100 KHZ . In all, 3500 points of high speed heat transfer data were recorded in each channel giving over 7 milliseconds of data points at intervals of 2μ sec. A detailed description of the instrumentation has been reported elsewhere by Doorly and Oldfield (1985a) and Ashworth, et al., (1985).

The unsteady NGV/rotor wake interaction events expected in a real engine or rotating experiment were simulated by passing the wakes from 2 mm diameter bars attached to a disk rotating upstream of the cascade. This method of simulation, developed and described by Doorly and Oldfield (1985b) is illustrated in Figure 2. The effective wake passing frequency was reduced for this experiment to 435 HZ (well below realistic engine conditions) to allow time for detailed observations of the boundary layer condition between wake events but still fast enough to capture over 3 bar passing cycles. This allowed ensemble averaging and permitted repeatability evaluations to be made. The bar rotation speed was maintained at levels which allowed the correct inlet velocity triangle conditions to be assured. The tests reported herein were run with subsonic bar relative Mach number, however, to eliminate the effects of shock wave interactions which would be present in the real engine rotating environment

Experimental Results - Natural Transition

The mean (steady state) aerodynamic and heat transfer conditions of the blade profile tested in the present experiment have been measured and reported elsewhere by Ashworth et al. (1987). The results indicated that the flow undergoes a fairly constant acceleration through transonic conditions to a point well back on the suction surface (X/S > 0.6) where the acceleration parameter then becomes mildly adverse. The heat transfer records indicated that for the low turbulence free stream case (no turbulence grid) the boundary layer remained laminar over the entire instrumented section. The high free stream turbulence case, however, clearly indicated a transitional boundary layer extending over much of the blade surface region where the closely spaced heat transfer gauges were located.

Although the transitional nature of the boundary layer in the high free stream turbulence case was clearly indicated by the gradually rising mean heat transfer levels along the surface, the wide-bandwidth fast sampled data gave a clearer picture of the physical processes involved, e.g. Figure 3. In several of the figures presented by Ashworth et al. (1987), discrete, rapidly changing excursions in the heat transfer signals were seen to rise above the laminar levels, grow in extent and eventually merge into a continuous higher level signal. This behavior learly consistent with the often observed turbulent spot growth model of the final (3-D) stages of boundary layer transition as reported e.g. by Schubauer and Klebanoff (1956). The ability of the instrumentation to respond to turbulent spot development permitted quantification of the process to be made. Specifically, this analysis included assigning an intermittency value to the process by selecting a threshold value above the laminar signal and counting the fraction of time the signal was above this (see Ashworth et al. [1987]). By cross- correlation analysis of adjacent channels, the same authors were also able to estimate mean convection rates of the disturbances from gauge to gauge. The existence of data in this form permitted detailed comparisons to be made with the numerical models of transition discussed below.

<u>Experimental Results - Transition With Wake Passing</u>

The second part of the experimental program repeated the undisturbed tests discussed above with wake disturbances superimposed on the flow using the rotating bar arrangement described earlier. Shown in Figure 4 is a series of wide-bandwidth signals from consecutive channels showing clearly a single wake-passing event and an extent of undisturbed boundary layer heat transfer rate signals. On the same figure is included the heat transfer signals from the low free-stream turbulence results, i.e. the laminar boundary layer levels of heat transfer rate (Nusselt number).

$$\text{where } Nu = \frac{\dot{q}}{T_0 - T_w} \frac{c}{k}$$

and c = tangential chord

k = thermal conductivity

T_0 = total temperature

T_w = wall temperature

$\dot{q}$ = measured heat transfer rate

Again clear evidence of transitional turbulent spot activity is seen in the regions of the output removed from the wake region. Although for clarity, only one wake is shown in Figure 4, several wake events were captured by the fast data scan and ensemble averaging was therefore possible. Figure 5 is an example of one such averaging process. The ensemble averaging process highlights additional structure not evident in the single unaveraged signals, e.g. the double peaked nature of the wake signal in the earlier channels of the blade passage. This is consistent with the existance of coherent structure remaining from the vortex shedding pattern from the rotating bars. It can also be observed from the data in Figure 3 unaveraged data that the transition process in the region between the wakes appear to develop in much the same way as the process in the naturally transitional boundary layer reported earlier.

Although the data did not permit the accurate estimation of leading edge and trailing edge propagation rates, it was possible to estimate mean spot convection rates by cross-correlation analysis of adjacent channels. The results are shown in Figure 6 along with the trajectories predicted using the commonly observed values of leading edge and trailing edge propagation rates from low speed turbulent spot data (e.g. Schubauer and Klebanoff [1956]). The data generally falls between the two outer limits as might be expected with mean data.

Numerical Model-Wake Passing

The first part of the numerical modelling effort concentrated on predicting the path the rotating bar wake was expected to take as it encountered the blade row and progressed through the passage. The next section below discussed a proposed model for the random generation, growth and convection of turbulent spots. The two models are then combined to give a prediction which can be compared with the data reported herein.

The wake itself is nearly 2-dimensional in form, expected to vary only slightly in height along the bar span due to the slightly varying Reynolds number as the bar relative velocity changes (with radius). A two-dimensional model is assumed using conditions at bar mid-point. The procedure follows that described by Doorly (1983) which has now been automated and also allows for a spreading wake width being proportional to the square-root of the distance from the bar along the line of U_{rel} with the constant of proportionality derived from a data base of wake measurements. The wake is then convected through the blade row passage using an inviscid time marching flow field calculation based on a method developed by Denton (1983). U_{rel} is is assumed constant and the center-line of the undistorted wake is calculated from a specified bar position and the width added as described above. The wake is shifted back in time so that the bar will return to its correct position following the marching process of the prediction. From this initial position, elements of the wake are convected by small time steps using the local velocity interpolated from the predictions until the bar reaches the specified location. The differential velocities in the flow field cause distortions of the wake along its length and across its width as it is accelerated through the passage. The results of such a calculation are shown in Figure 7. The positions of the wake agrees well with the positions shown on schlieren photographs presented by Schultz et al. (1986).

It was then possible to compare the wake passage prediction from the time marching (striped air calculation) scheme with the observed suction surface heat transfer record. It should be emphasized again that the prediction for the wake passage is based on an inviscid flow field calculation whereas the observed heat transfer effects are measured on the blade surface, at the base of the blade viscous boundary layer. The results are shown in Figure 8 given predicted and observed wake path for the leading and trailing edge as a trajectory in an x-t diagram. The figure shows excellent agreement for the leading edge prediction with an expected difference in trailing edge prediction. Also shown on Figure 8 are predicted propagation trajectories for the leading and trailing edge of the wakes based simply on a range of assumed fractions of actual local free streams velocities. The values of $0.88U_\infty$ and $0.5U_\infty$ were selected from values commonly accepted for turbulent spot leading and trailing edge propagation rates e.g., Schubauer and Klebanoff (1956). The time-marching prediction, of course, closely follows the $1.0U_\infty$ value with small differences due to the wake spreading included in the striped-air model. The leading edge data closely follows predicted trajectories ($0.88U_\infty$-$1.0U_\infty$) whereas the trailing edge data seems to closely follow a $0.5U_\infty$ trajectory i.e., the wake generated patch of turbulence in the boundary layer propagates at rates closely following many observations of naturally occurring (and artificially generated) turbulent spots in low speed flows.

Numerical Model - Natural Transition

A generalied model time-marching scheme was eveloped (see Ashworth [1987]) for the prediction of transitional intermittency using the turbulent spot model proposed by Emmons (1951) and extended later by Narisimha (1957) and Chen and Thyson (1971). This model allowed for turbulent spots to be generated randomly at any point on the blade surface and subsequently propagated downstream at an arbitrary growth angle and leading edge and trailing edge propagation rate (as a fraction of free stream velocity). The self-similar spot growth characteristics were then combined with the blade geometry information and thin film sensor locations to predict the fraction of time the spots contact with the films (or part thereof). This would then give predictions of intermittency consistent with what would be measured with the sensing elements in these experiments. The model requires input data for:

i) velocity at the given streamwise location $U_\infty(x)$

ii) the scaling parameter (N_3), mean (μ) and variance (S) of the random source rate function g(x)

$$g(x) = -\frac{N_3}{\sqrt{2\pi s}} \exp\left(-\frac{(x-\mu)^2}{2s}\right)$$

iii) spot propagation parameters

$$\sigma = \tan \alpha \left(f_t^{-1} - f_\ell^{-1}\right)$$

where α is spot spreading angle and F_t and F_ℓ are the trailing edge and leading edge spot propagation velocities (as a fraction of free stream velocity)

iv) surface geometry and gauge length and location.

A typical plan view of the model surface (with sensing elements in place) showing the coverage of turbulent spots generated by the above procedure is shown in Figure 9 for a frozen instant of time. Also shown on the surface is the assumed foot print of a wake passing over the surface. In this way an effective intermittency can be estimated by summing the portion of the gauge covered by turbulence (either from a wake or a spot). Intermittency values can then be easily converted to Nusselt number values by summing the contributions of laminar Nusselt number and turbulent Nusselt numbers for each gauge.

$$Nu = (1-\gamma)Nu_\ell + \gamma Nu_t$$

where Nu_ℓ and Nu_t are laminar and turbulent Nusselt numbers respectively predicted (in this case) by an integral method. This results in heat transfer predictions such as shown in Figures 10 and 11 for some selected sensor locations. This clearly shows the similarity between the data presented with the prediction method.

Conclusions

It was shown that wide-bandwidth heat transfer instrumentation was able to track trajectories of both unsteady wake passing events and transitional turbulent spots on a turbine airfoil under a simulated gas turbine environment. The observed behavior was accurately modeled by a time-marching simulation of both the inviscid wake passing interaction and the random generation and growth of turbulent spots based on the well established low speed theory and observations of the final 3-D stages of boundary layer transition.

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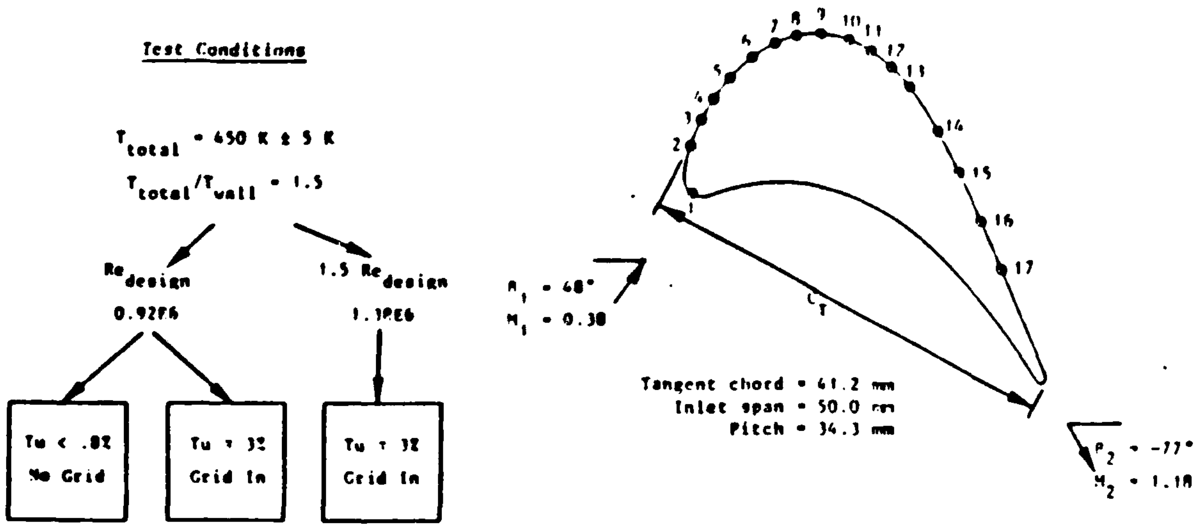

Heat Transfer Gauge Locations

Model Point	x/s
1	0.00
2	0.05
3	0.12
4	0.15
5	0.19
6	0.24
7	0.28
8	0.31
9	0.35
10	0.39
11	0.43
12	0.47
13	0.51
14	0.58
15	0.65
16	0.73
17	0.81

Figure 1 - Instrumented Model Details and Test Conditions.

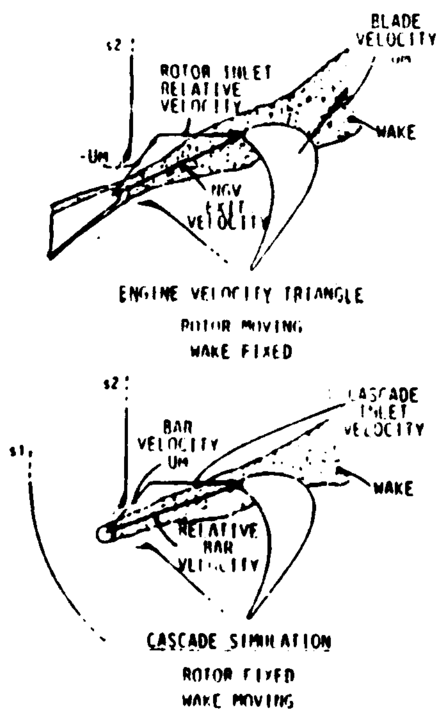

Fig. 2 Illustration of the comparative velocity triangles for the engine and cascade simulation of the NGV/rotor interaction.

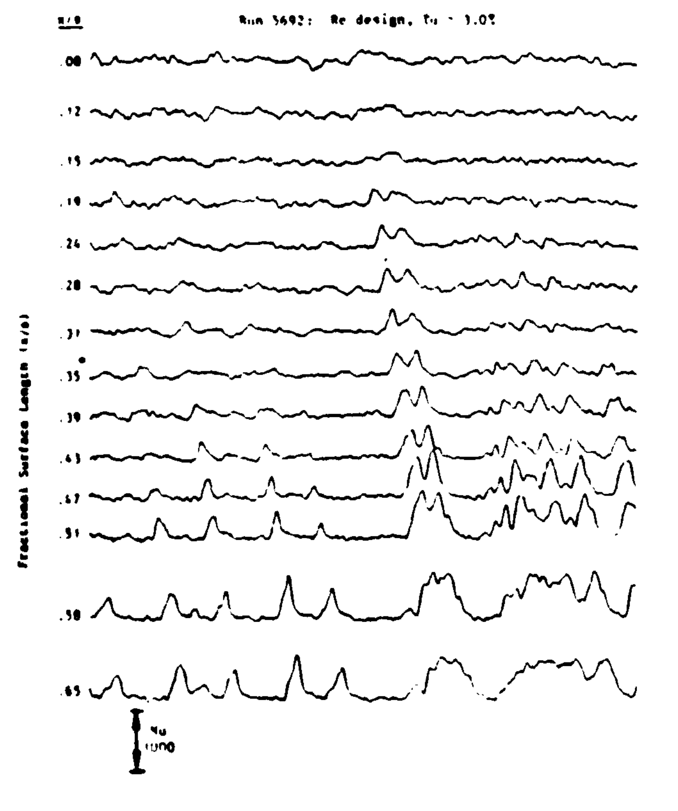

Figure 3 - Natural Transition Heat Transfer Progression Along the Model Surface.

Figure 4

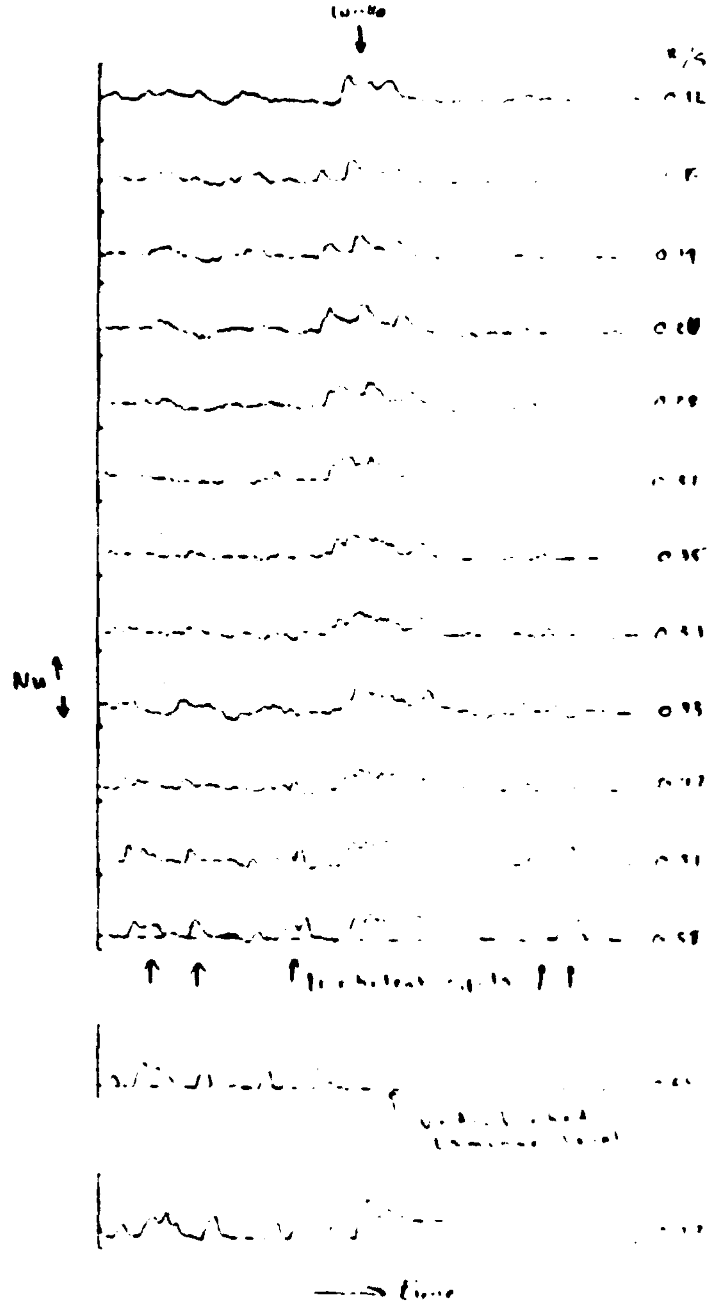

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Figure 5

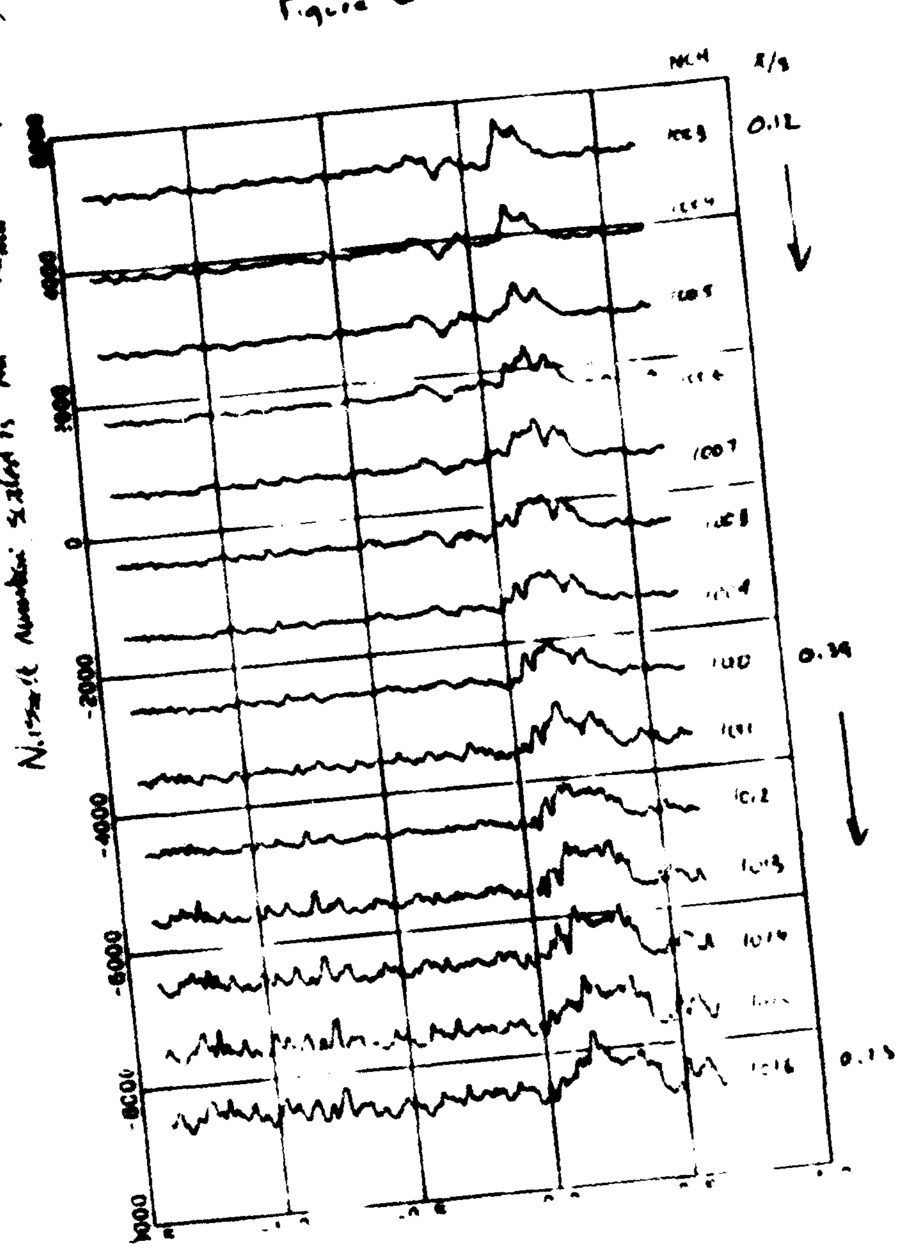
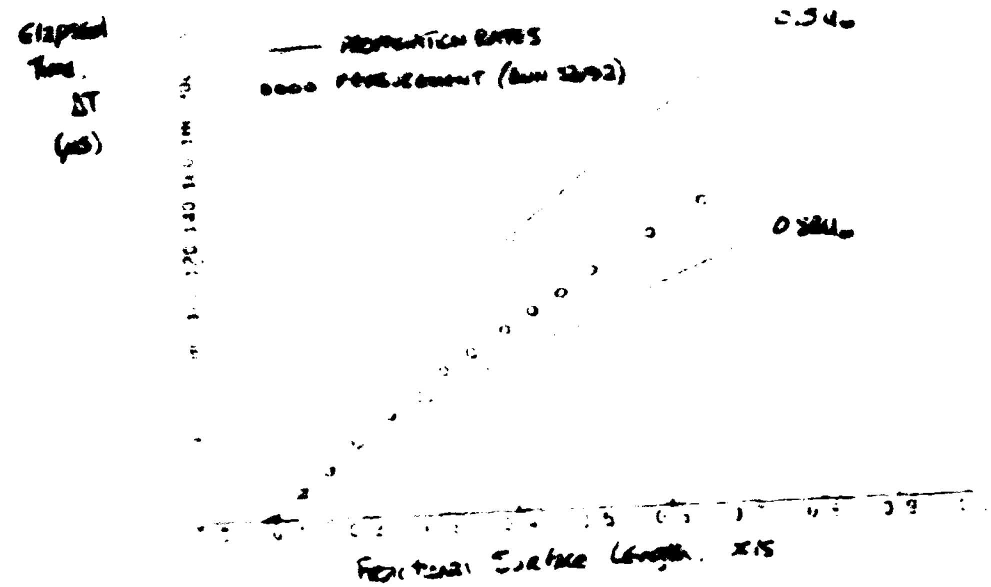
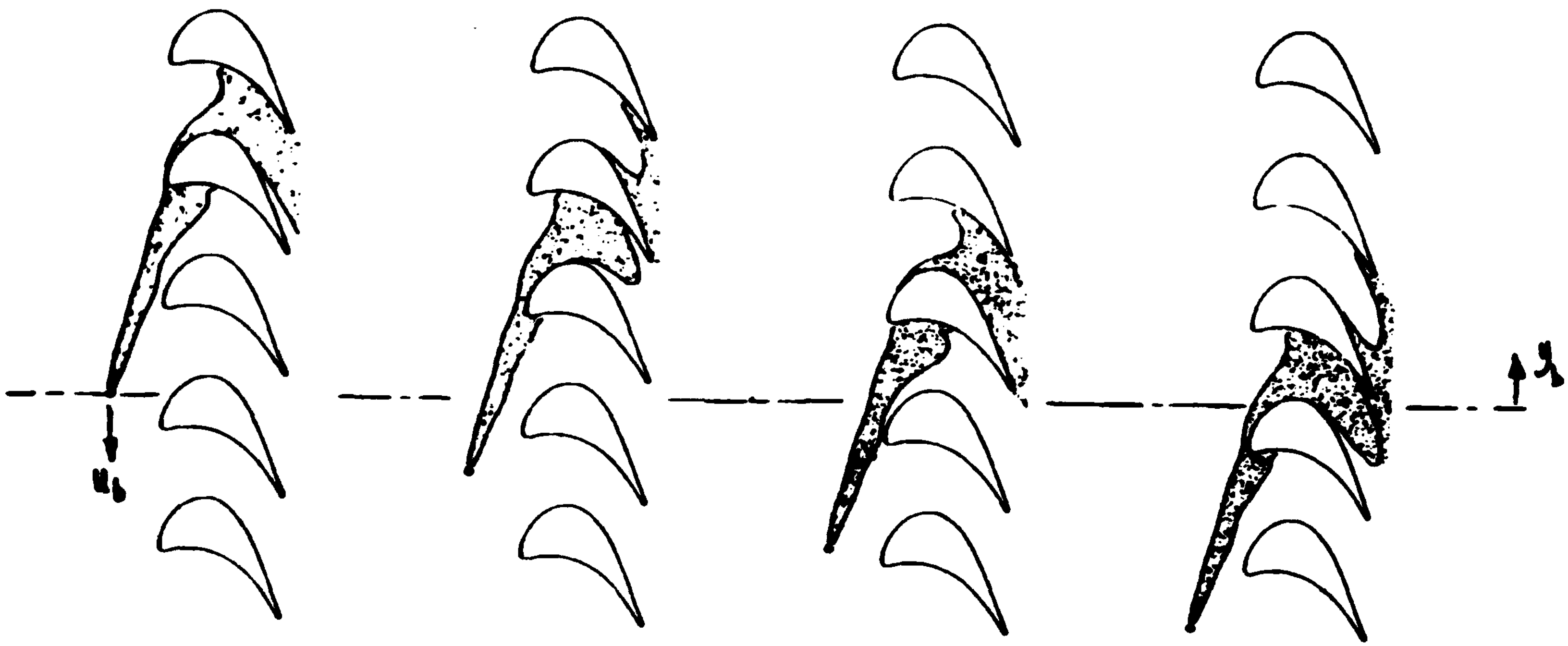


Figure 6



Comparison of Measured Convection Rate for ... Transition ... Convection Rate



y_s (mm)	0	-20	-40	-60
θ (°)	0	8	16	24

Striped-air calculation for four positions of the bar.

Figure 7

Figure 8

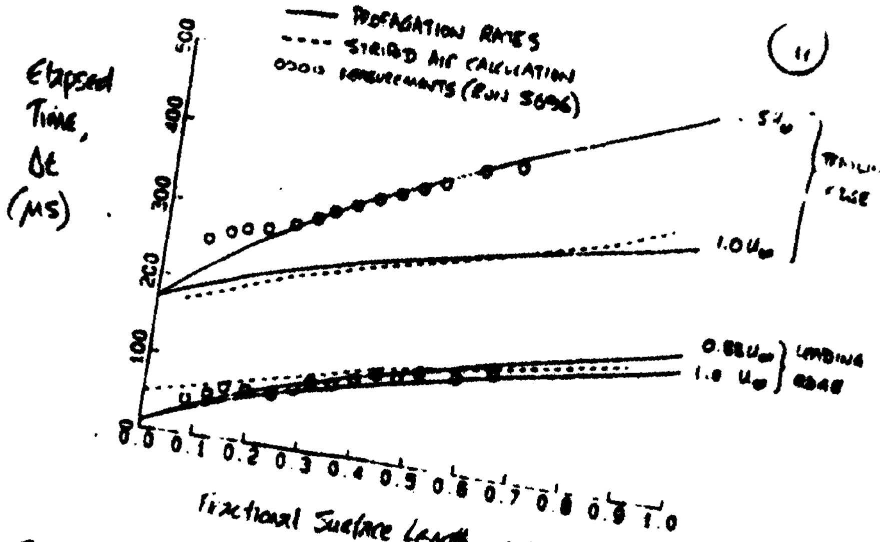


Fig _ Comparison of Measured Leading and Trailing Edges of nozzle-induced turbulent patch with prediction.

Fig. 9 Plan view - Typical Timeframe of unsteady wake and turbulent spot activity

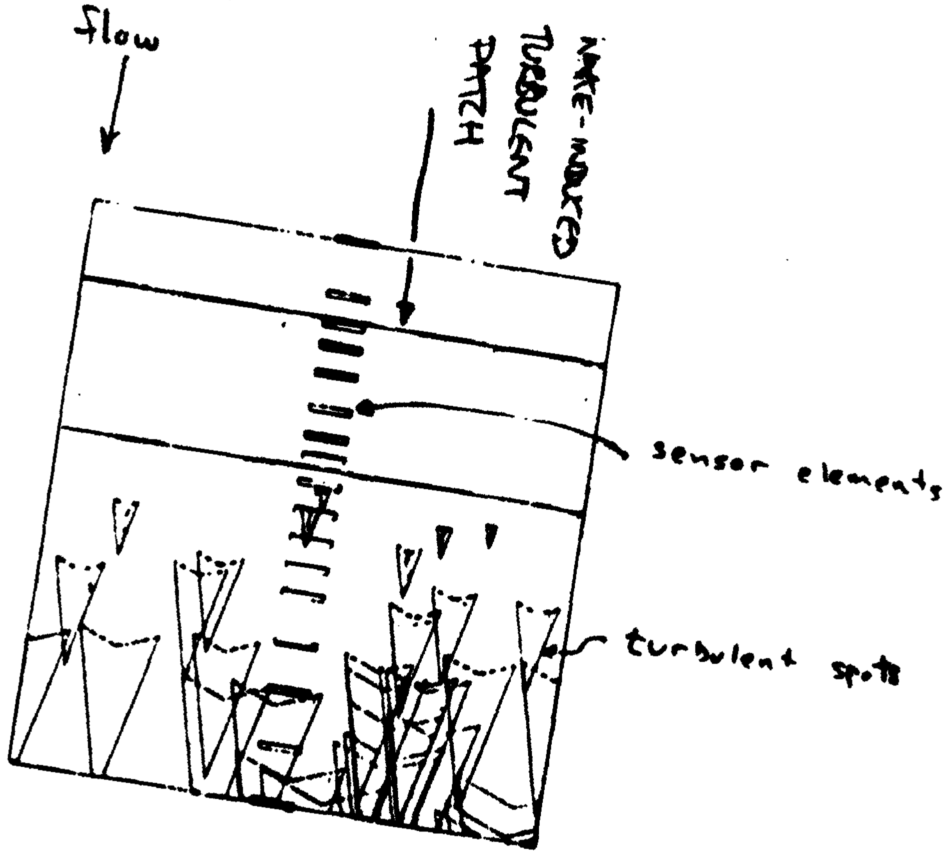


Figure 10 Natural Transition

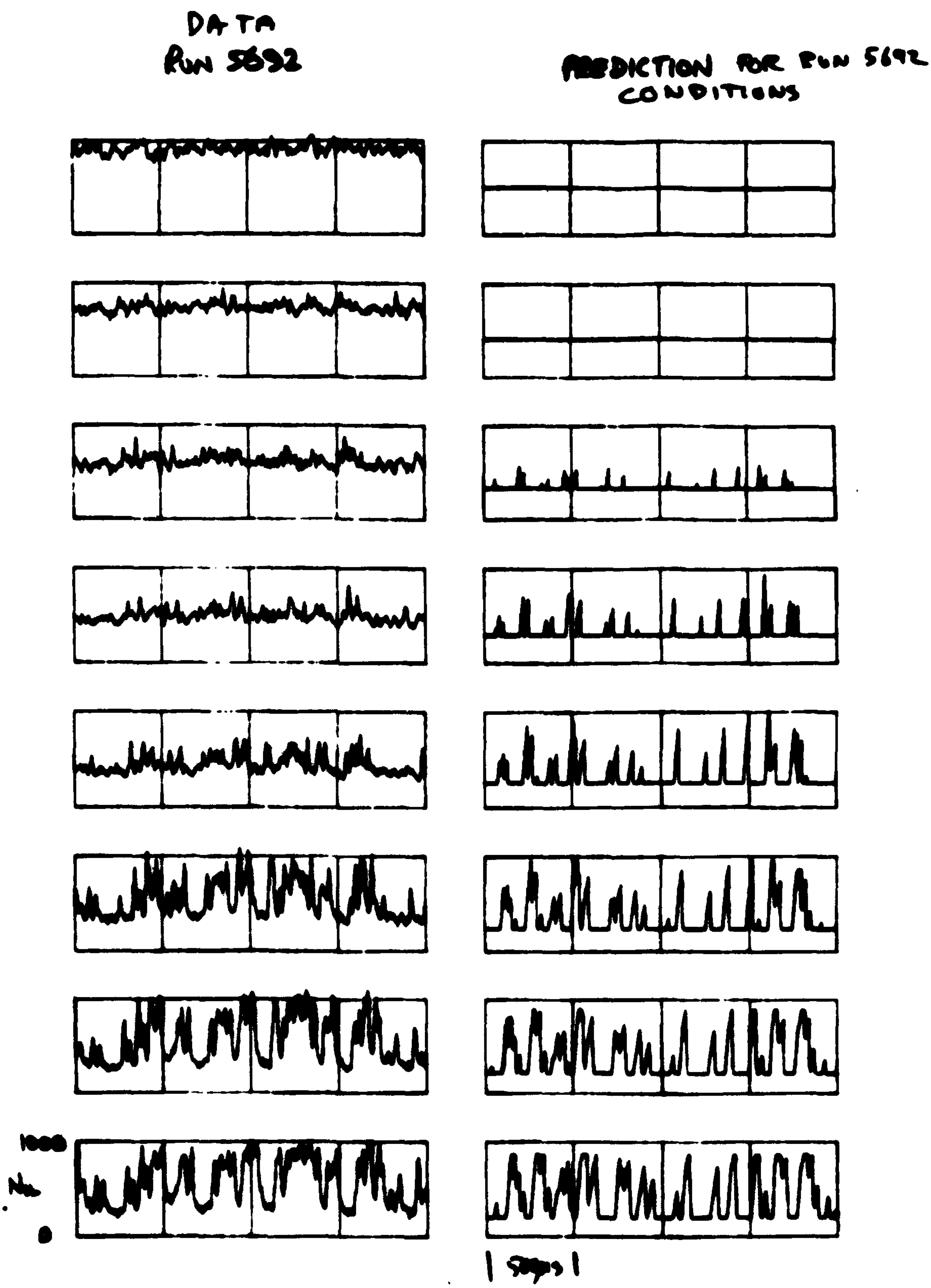
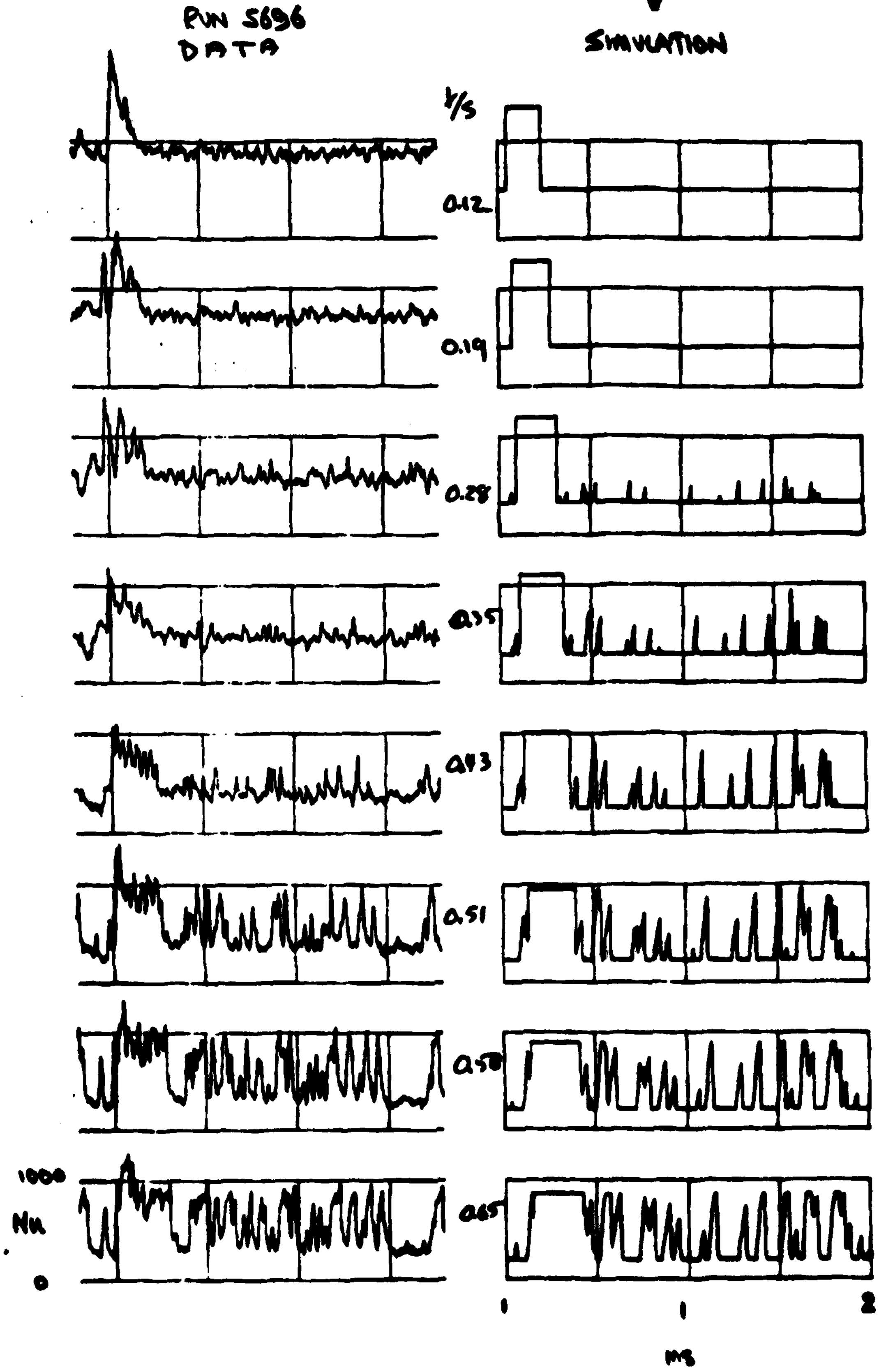


Fig. 11 Wake Passing/transition

Prediction for Run 5696 Conditions



Prediction Parameters

$\alpha = 10^\circ$ $\mu = 10$ mm

$f_s = 0.88$ $\sigma = 1$ mm

$f = 0.5$

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